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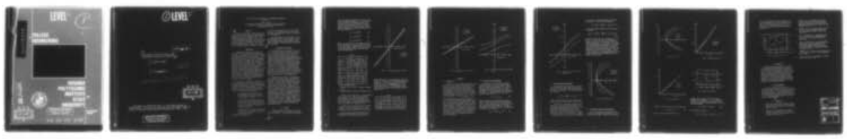

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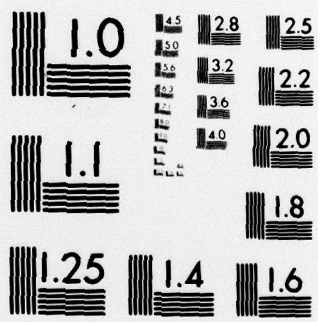


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# THE EFFECTS OF PITCHING RATE ON THE HYDRODYNAMIC PROPERTIES OF HYDROFOILS

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## Abstract

Little or no test data is available to verify theory predicting lift, drag and pitching moment of a hydrofoil in the presence of pitching motion commonly encountered in hydrofoil craft. The present paper presents the results of a wind tunnel investigation of the effects of pitching motion on two hydrofoil configurations. The results are compared to prediction techniques given in the U.S.A.F. DATCOM (Ref. 1). Finally, a verified force and moment prediction technique is presented.

## 1. Introduction

A great deal of emphasis is placed on the pitching motions of conventional displacement ships, i.e., on methods of prediction, and methods of reducing the severity of these motions. These same motions occur in no less a degree on high performance hydrofoil craft, in this case however pitching motion is encountered by the hydrofoils, rather than the hull proper. Unfortunately, in dynamic simulations of these craft, the effects of pitching motion are notably absent. (References 2 and 3) This is due to the lack of an experimentally verified theory on the hydrodynamic properties of hydrofoils in pitching motion. Such a theory would have wide ranges of application in stability, control and seakeeping studies of hydrofoil craft. Further areas of application immediately come to light, including studies on ship rudders in yawing motion, submarine control surfaces in both pitching and yawing motions and also in S.W.A.T.H. ship stabilizer and strut surfaces in both pitch and yaw.

A survey of the literature indicates relatively little work in this area. Ribner (Ref. 4) gives approximate methods of obtaining both static and dynamic derivatives, but these are limited to triangular planforms with low aspect ratios. Toll and Queijo (Ref. 5) presented the approximate method of considering the hydrofoil lift and moments to be the sum of three components,

1. an increment of lift and pitch due to the aerodynamic center being offset from the center of gravity, about which pitching motion is defined,

2. an increment of lift and pitch due to the curvature, approximated by assuming the curvature to cause the foil to behave as if it had a circular camber, and assuming the additional lift to act through the midcord,

3. an increment of lift and pitch due to the additional lift of the above increment, acting through the quarter chord, but in the opposite direction.

This method is presented for use in the DATCOM (Ref. 1). Calculated dynamic derivatives using this method are compared to the data from the current investigation.

The present paper gives the results of curved flow wind tunnel tests on one low aspect ratio and one moderate aspect ratio hydrofoil. These data are then used in a proposed semi-empirical model of hydrofoil properties under the influence of pitch rates.

## 2. Experimental Procedure

The investigation was conducted in the V.P.I. & S.U. subsonic stability wind tunnel using the 6' x 6' curved flow test section. In this section, the vertical tunnel walls are physically curved to provide flow angularity while wire screens creating a dynamic pressure gradient across the test section provide the required velocity distribution to complete the simulation of curved motion. Although the test section walls may be formed to a wide range of curvatures the number of wire screens available limit the achievable turn rates to four. Defining a nondimensional pitch rate as $q' = q\bar{c}/2V$, where $q$ is the dimensional pitch rate, $\bar{c}$ is the hydrofoil mean aerodynamic chord and $V$ is the freestream velocity, pitch rates of 0.0387, 0.0572, 0.0787, and 0.1115 (based on a chord of 4 feet) can be attained. A more detailed description of the facility together with its theory of operation is given in Reference 6.

Although the test section is constructed to give yaw rates, pitching may be simulated by rotating the hydrofoil 90 degrees to an upright position. In the present investigation, two hydrofoils were tested in two curvatures numbers two and four, and straight flow. Table 1 gives the various physical particulars of each foil together with the pitch rates corresponding to the tunnel curvatures at which the foils were tested. The foils were mounted vertically on a strut in the tunnel on top of a 6' x 4' ground board with approximately .25 inches clearance above the board. The ground board serves as an endplate to effectively double the aspect ratios of the models. At each curvature, the models were rotated up to angles of attack of plus or minus 10 degrees in increments of two degrees. Mounted on the strut inside each foil was a six component strain gauge. At each angle of attack forces and moments were read and reduced using a Hewlett Packard Data Acquisition System.

## 3. Results

In the present work, the particular interest is on the behavior of lift, drag and pitching moment in curved flow. These quantities were reduced

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from strain gauge measurements by including calculation of blockage effects due to the presence of the large hydrofoils (compared to tunnel cross sectional area) and the calculation of bouyancy terms due to the presence of the radial pressure gradient caused by the tunnel curvature. These forces and moments were nondimensionalized by the following conventions;

$$C_L = L/(1/2)\rho V^2 S \qquad (1)$$

$$C_D = D/(1/2)\rho V^2 S \qquad (2)$$

$$C_m = m/(1/2)\rho V^2 S \qquad (3)$$

where L, D, and M are the lift, drag and pitching moment, respectively; S is the planform area, and $C_L$, $C_D$, and $C_m$ are the nondimensional lift, drag and pitching moment. Table 1 lists the location of the reference center about which the pitching moment was measured.

TABLE 1.

| | Foil 1 | Foil 2 |
|---|---|---|
| Section | NACA 0020 | NACA 0020 |
| Span | 2.17ft.(.83m) | 1.4ft.(.34m) |
| $\bar{c}$* | 1.86ft.(.57m) | 2.37ft.(.88m) |
| Taper ratio | 0.5 | 1.0 |
| AR | 2.9 | 1.45 |
| H** | 1.125ft.(.35m) | 0.75ft.(.23m) |
| Sweep of ¼c | 20.34 (deg.) | 0.0 (deg.) |
| $q_2'$*** | 0.0266 | 0.0339 |
| $q_4'$*** | 0.052 | 0.066 |

* Mean Aerodynamic Chord

** Distance from foil Vertex to moment reference center

*** Nondimensional pitch rate at curvature 2 and 4

Figures 1 and 2 show plots of $C_L$ versus angle of attack for foils 1 and 2 for all three curvatures tested. The nonzero intercept of the zero curvature line is due to the presence of some angle of attack due to misalignment of the foils in the tunnel. In subsequent data analysis these misalignments were treated as tares.

Figures 3 and 4 are plots of Cm versus angle of attack for foils 1 and 2 showing all three curvatures. Foil misalignment is indicated by a repeated upward shift of the zero curvature data.

From this data, stability derivatives were calculated and compared to those predicted by the method of Toll and Queijo as given in the

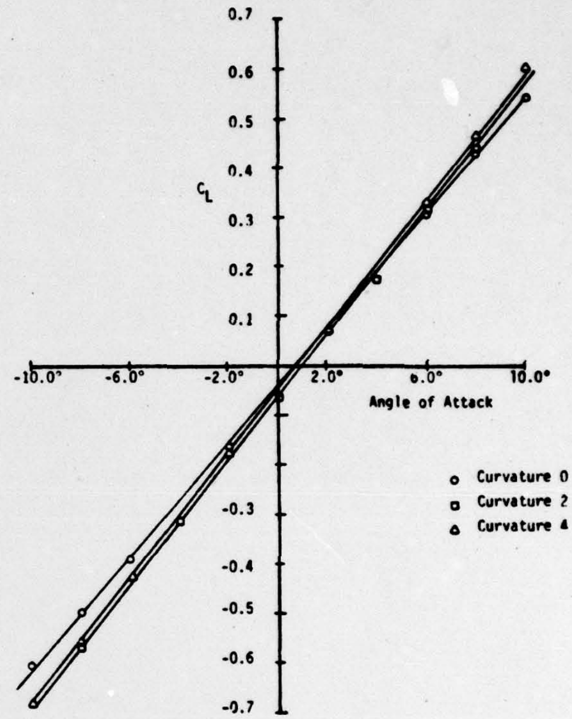



Figure 1. Lift Coefficient vs. Angle of Attack for Foil 1.

DATCOM (Reference 6). These comparisons are given in Table 2. Examination of these shows good agreement of V.P.I. calculated $C_{L_\alpha}$ and $C_{m_\alpha}$ with the DATCOM predictions. The agreement of V.P.I. calculated $C_{m_\alpha}$ and $C_{L_q}$ with DATCOM methods is seen to be relatively poor. This is probably due to a difficulty in calculating the location of the aerodynamic center.

TABLE 2.

| | V.P.I. & S.U. | | DATCOM | |
|---|---|---|---|---|
| | Foil 1 | Foil 2 | Foil 1 | Foil 2 |
| $C_{L_\alpha}$(/rad) | 3.34 | 1.60 | 3.41 | 1.57 |
| $C_{m_\alpha}$(/rad) | 0.54 | 0.54 | 1.23 | 0.32 |
| $C_{L_q}$(/rad) | 0.0 | 0.0 | -1.436 | -0.245 |
| $C_{m_q}$(/rad) | -0.79 | -0.54 | -0.72 | -0.62 |

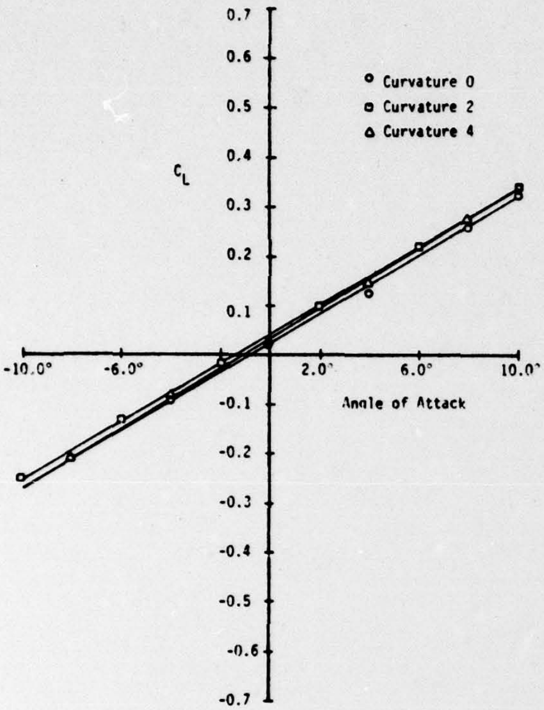



Figure 2. Lift Coefficient vs. Angle of Attack for foil 2

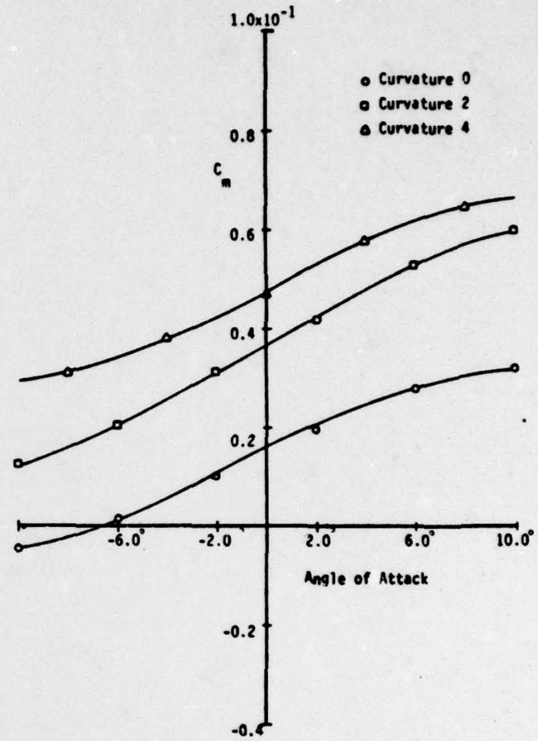



Figure 3. Pitch Moment Coefficient vs. Angle of Attack for foil 1.

## 4. Modeling

### 4.1 Introduction

Currently, in linear dynamic simulations, the vehicle forces and moments are expanded using a Taylor series and taking the motions, accelerations and displacements to be perturbation variables (Ref. 7). Terms of order greater than one are generally neglected in the Taylor series. In an expansion of the lift coefficient, the assumed form may be, $C_L = C_L(\alpha, q', r', \ldots)$, and the corresponding Taylor expansion, $C_L = C_{L_0} + \partial C_L/\partial\alpha*\alpha + \partial C_L/\partial q'*q' + \ldots$ etc., where $\left.\frac{\partial C_L}{\partial \alpha}\right|_0$ is the stability derivative. The first two terms of this expansion are generally well understood and have a very clear physical interpretation. However, the third term is somewhat less well understood. Essentially the effects of pitch rate are grouped together in one term (Ref. 8) and it is difficult to gain insight into the origins of the basic hydrodynamics. The intent of the proposed models is to allow description of the effects of pitching motion on hydrofoils in a manner that arises more naturally from the data and also allows these effects to be expressed in terms of explicit parameters.

### 4.2 Lift Coefficient Development

To model the lift coefficient to include pitching effects, the first two coefficients of the Taylor expansion in angle of attack were assumed to be arbitrary functions of q'. This allows the camber inducing effect of pitching as suggested by Toll and Queijo (Ref. 5), as well as the behavior of the conventional lift curve slope, to be seen. The model describing the lift coefficient linear in $\alpha$, is:

$$C_L = C_{L_0} + \alpha C_{L_\alpha} \qquad (4)$$

where, in general, the intercepts $C_{L_0}$ and the slopes $C_{L_\alpha}$ are functions of the steady pitching rate q'. From figures 1 and 2 it is apparent that $C_{L_0}$ is very nearly independent of q' and $C_{L_\alpha}$ is likewise constant with changine q'. With both coefficients of equation 4 constant, the derivative with respect to q' becomes:

$$C_{L_q}' = \partial C_L/\partial q' \Big|_{\alpha=0} = 0 \qquad (5)$$

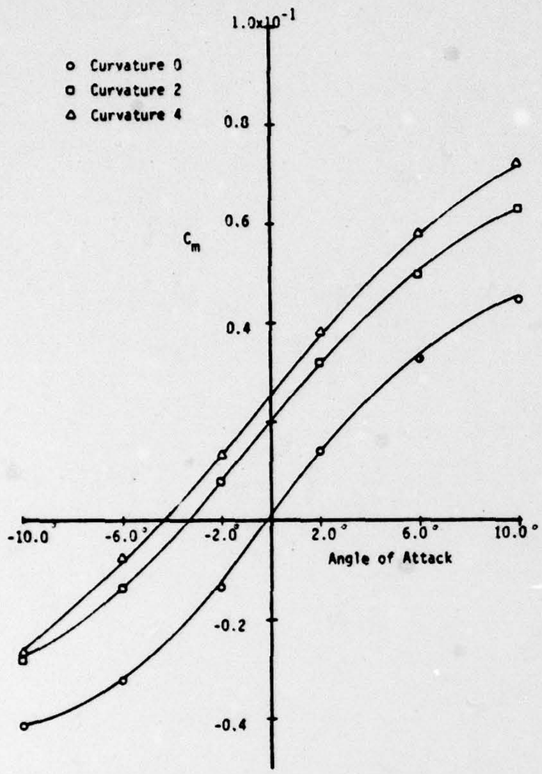



Figure 4. Pitch Moment Coefficient vs. Angle of Attack for foil 2

## 4.3 Drag Coefficient Development

In modeling the drag coefficient, the drag polar equation was used, allowing the drag to be expressed as a function of zero lift drag and lift due to induced drag. The following equation was then used:

$$C_D = C_{D_o} + \frac{k}{\pi AR}(C_L - C_{L_{o_2}})^2 \qquad (6)$$

where, in general, $C_{D_o}$, $C_{L_o}$ and k are functions of the pitch rate q' and AR is the aspect ratio.

Figures 5 and 6 are plots of drag polars of each foil. These plots allow isolation of the parameters, $C_{LD_o}$ and $C_{L_{O2}}$ that vary with q'. Further manipulation of the data to identify a variation of the parameter k with q' led to ploting the drag polar in the form; $(C_D - C_{D_o})$ against $(C_L - C_{L_o})$. This form allows k to appear as the slope of the now linear curve. As seen in figures 7 and 8, k turns out to be independent of pitch rate. Therefore the model describing drag behavior in pitching motion becomes:

$$C_D = C_{D_o}(q') + \frac{k}{\pi AR}(C_L - C_{L_o}(q'))^2 \qquad (7)$$

and the corresponding derivative with respect to q' becomes:

$$\partial C_D/\partial q' = \partial C_{D_o}/\partial q' - \frac{2k}{\pi AR}(C_L - C_{L_o})\,\partial C_{L_o}/\partial q' \qquad (8)$$

Figure 9 shows $C_{L_o}$ and $C_{D_o}$ as functions of q' for each foil. Using this plot, the derivatives $\partial C_{D_o}/\partial q'$ and $\partial C_{L_o}/\partial q'$ may be calculated and employed in equation 7 to find $\partial C_D/\partial q'$. It is seen that the dependence of $C_{L_o}$, $C_{D_o}$ and k are strongly influenced by physical parameters of the foils such as aspect ratio, taper ratio, thickness, etc. Unfortunately insufficient data was collected to completely characterize this influence. The collection of data in which these parameters are varied systematically would generalize the present approach and allow an extended semi-empirical method to be developed.

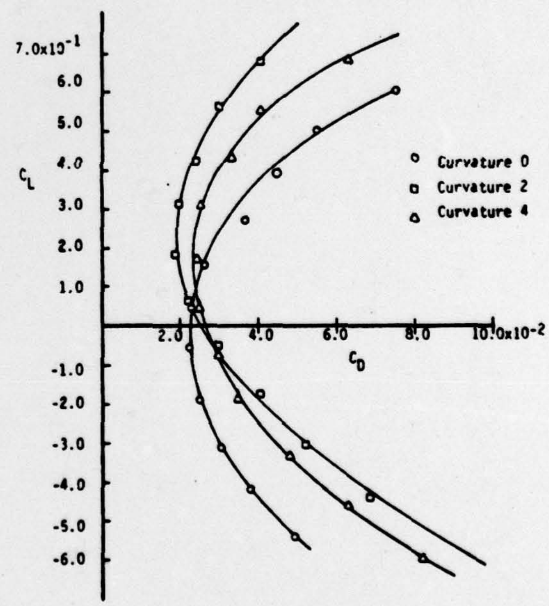



Figure 5. Drag Polar for foil 1.

## 4.4 Pitch Moment Coefficient Development

The pitching moment was modeled using an equation of a form analogous to that used in the lift coefficient model. Therefore the following

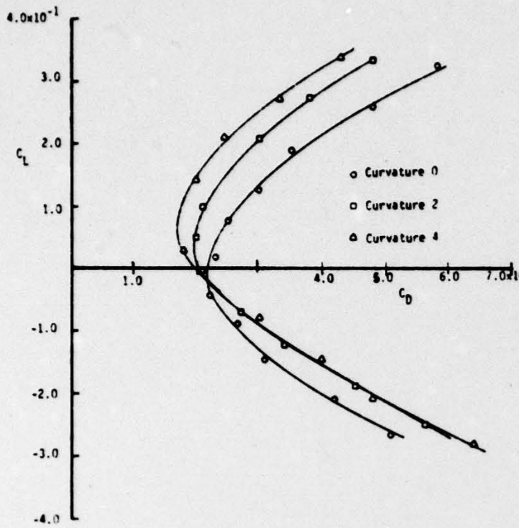



Figure 6. Drag Polar for foil 2.

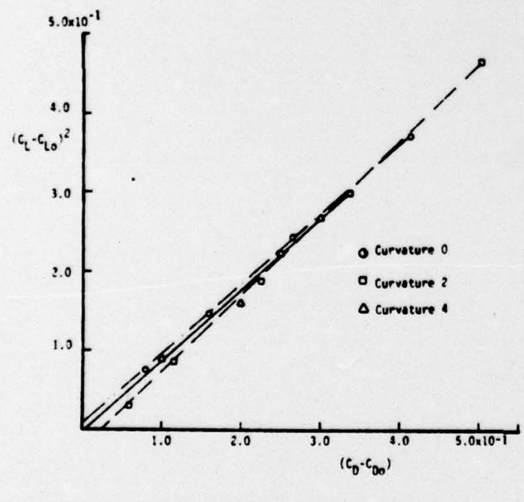



Figure 7. Linearized Drag Polar for foil 1.

equation, linear with angle of attack was used:

$$C_m = C_{m_o} + C_{m_\alpha}\,\alpha \qquad (9)$$

where, $C_{m_o}$ and $C_{m_\alpha}$ are functions of q'.

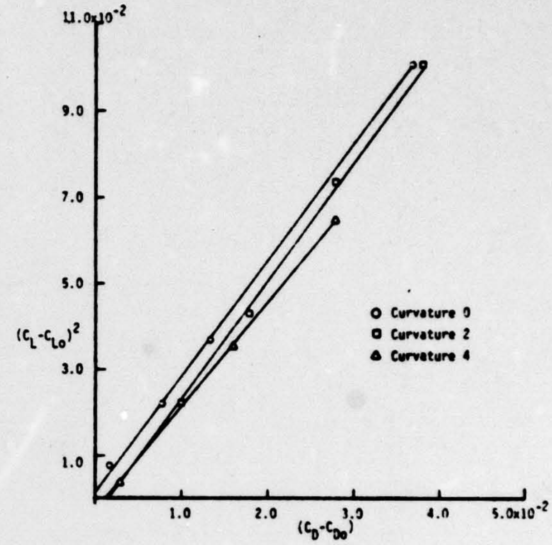



Figure 8. Linearized Drag Polar for foil 2.

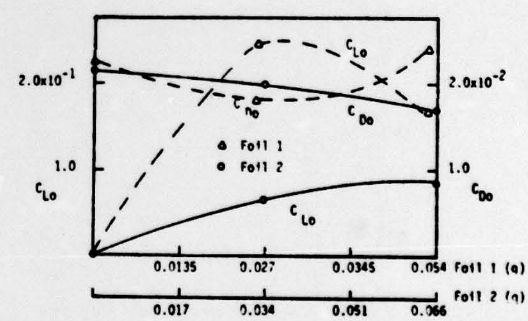



Figure 9. $C_{Do}$ and $C_{Lo}$ for foils 1 and 2.

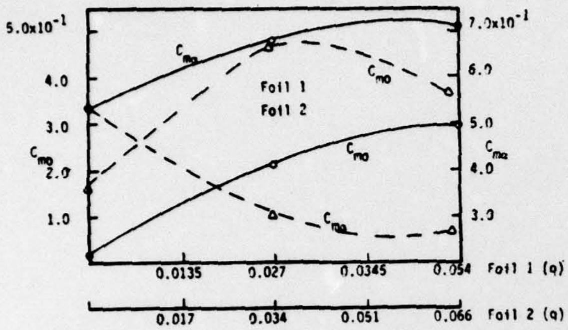
Figures 3 and 4 indicate that both of these parameters are dependent on q'. This dependence is shown for the two foils in figure 10. The model describing pitching moment behavior in pitching motion becomes:

$$C_m = C_{m_o}(q') + C_{m_\alpha}(q')\,\alpha \qquad (10)$$

and the derivative $C_{m_q}'$ is:

$$\partial C_m/\partial_q' = \partial C_{m_o}/\partial_q' + \partial C_{m_\alpha}/\partial_q'\,\alpha \qquad (11)$$

As in the development of the drag coefficient, the terms in equation 10 may be calculated from the plot of the respective functions (Figure 10). Again it is seen that both $C_{m_Q}$ and $C_{m_\alpha}$ are strong functions also of the physical parameters of the foils.




Firure 10. $C_{m_\alpha}$ and $C_{m_Q}$ for Foils 1 and 2.

## 5. Conclusions

Wind tunnel data of hydrofoils in curved flow, simulating pitching motion, has been used in developing new models for describing the effects of pitch rate on hydrofoils. Expressions for lift, drag, and pitch moment coefficient have been presented which isolate the influence of pitch rate on parameters more commonly encountered and more physically tractable in hydrodynamic work. It is felt that continued investigations in which physical characteristics of the hydrofoils are varied would produce very useful extensions of the proposed models.

## 6. Acknowledgments

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